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by

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Submitted in partial fulfillment of
the requirements for the degree of

MASTER OF SCIENCE
IN
OPERATIONS RESEARCH

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Monterey, California

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This work is accepted as fulfilling

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from the

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ABSTRACT

The evaluation of a proposed submarine detection system by computer war gaming techniques is illustrated by a hypothetical example. A scenario is chosen, tactics and policies established, and the tactical simulation conducted. From the results of the simulation, minimum specifications for the system to attain a given level of effectiveness are drawn. Finally, a scale is made for comparison of this system with similar systems in terms of cost per day per mile of barrier.

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LIST OF ILLUSTRATIONS

TABLE OF SYMBOLS

Symbol	Definition or Meaning
a/c	Aircraft
onsta	Time a/c arrives on station
offsta	Time a/c goes off station
L	Length of legs (miles)
NL	The number of legs to be flown in a prescribed pattern
TS	Track spacing (miles)
DI	Drop interval between probes (miles)
θ	Field orientation (radians)
N	Number of submarines transiting the barrier in a given run
α	Relative course of the submarine to the field (radians)
DT	Time from submarine detection until relief a/c arrives on station
CT	Cycle time, time between scheduled a/c launches
WW	Width of wake or plan view of the wake diameter
X	Aircraft cost in terms of Dollars per Hour on station
Y	Probe cost in terms of Dollars per Probe dropped
Z	Readiness cost to maintain the alert status necessary for DT = 2 in terms of Dollars per Day
Z'	Readiness cost to maintain the alert status necessary for DT = 3 in terms of Dollars per Day

I

INTRODUCTION

Progress in submarine developments has outstripped submarine countermeasures to the extent that anti-submarine forces must now look for quantum jumps in effectiveness. They are forced to develop new techniques of detection or discover detection means which the submarine cannot avoid or neutralize.

Submarine detection devices, or sensors, as they are commonly termed, have become the nucleus around which the entire ASW force is built. The modification of a primary sensor system calls for a re-evaluation of both the force structure and the operating procedures. Often the nature of the system dictates the nature of the vehicle which will carry it. New systems sometimes require radical modifications of the parent vehicle and, in extreme cases, require that a new craft be built around the sensor.

Operational evaluation of new systems of this magnitude cannot take place until enormous sums of money have been invested. Some defects may not be evident in single plane operations but become significant with a group as big as a squadron. Conceivably, the nation could become economically committed to dependence on a system before it has been operationally tested. Proto-type installations and engineering mock-ups are useful for pointing out design defects. However, other techniques must be supplemented to determine operational specifications and to make preliminary estimates of the effectiveness of the proposed system. This paper proposes to show the use of a computer simulation of the tactical employment of an undeveloped sensor system. By means of an example,

necessary specifications to make the system operationally effective will be determined. A method for comparing this system with other systems designed for similar purposes will be discussed.

A hypothetical physical phenomena which the submarine cannot control will be proposed and a detector will be hypothesized. Descriptions of the phenomena will be kept as general as possible so as to impose minimum restraints on the engineering aspects of the development. Similarly, many variables and possible limitations will be omitted in the simulation. It is assumed that if any limitation proves to be unduly detrimental, it can be avoided by engineering adjustments.

It must be emphasized that all numbers used as values of critical parameters are just examples and have no implications of current equipment capabilities or readiness states.

In Chapter II, the hypothetical physical phenomenon to be exploited and the proposed sensor system are outlined. Chapter III contains a description of the model, including the tactical considerations and policies deemed necessary. The first section of Chapter IV is devoted to testing the model under several variations of parameters. If the overall results showed very little change with the variation of a particular parameter, that parameter was considered non-critical, a "reasonable" value was selected for it, and it was held constant thereafter. Similarly if a parameter had a "maximum" effectiveness at some value over the range considered for all combinations, it was also considered non-critical and held constant at this maximum value. In the latter part of Chapter IV, the results of variations of the critical parameters are discussed. In Chapter V, the effectiveness is cast in terms of cost for comparison with similar systems.

II

CHARACTERIZATION OF NATURAL PHENOMENON

The submarine of primary concern is one of the long range or long endurance type. In particular, a submarine equipped for launching ballistic missiles is a major adversary. These types are inherently very large and are built to travel at considerable depths. For this problem, consider the sea water at these depths to form a stationary, uniform body of liquid with little motion of its own. Such liquid would show a sharp disturbance when an object as large as a submarine passes through. The disturbance might take the form of a volume of turbulent water, a departure from the expected pressure pattern, a volume of ionized or otherwise chemically activated liquid, or a region of residue from the boat itself. Regardless of its nature, each of these disturbances will be assumed to have some common characteristics. Firstly, it will be assumed that the disturbance, which will be referred to as the "wake", is non-propulsive. In this respect a wake will be like tracks left by a vehicle over sand. In other words, the wake will only exist in water the submarine has traversed. The center of the wake will exist only along the submarine's path (considered in three dimensions). Secondly, it will be assumed that the disturbance will be propagated radially at an even rate. The decrease in intensity can then be considered to be a function of the radial distance from the actual path of the submarine. Now consider a sensor in the form of an expendable probe which will sense a disturbance above a pre-set level. For this sensor, or probe, the detection area can be assumed to be a cylindrical volume centered on the submarine's path. The radius of the cylinder is

determined by the sensitivity of the probe. Thirdly, it is assumed that the disturbance pattern will have a neutral or positive buoyancy. And finally, the disturbance will be assumed to persist at a point at the required level for detection as a function of time, independent of the speed of the submarine or other propagation factors. This implies that the disturbance behind a submarine will exist at or above the detection level threshold for a set length of time. How far the submarine has traveled since it initiated the disturbance at that point depends on the submarine's speed. Hence, the length of the wake at any time is the product of the sub speed and the wake persistence. Thus, the wake can be approximated by a long cylindrical volume behind the submarine with the length of the cylinder being a function of the sub speed, and the radius a function of the probe sensitivity.

The system description of "expendable probes" and the requirement that the probe be in contact with the wake for a detection characterize aircraft launched detectors. It is, therefore, hypothesized that a "Request For Proposal" be sent out for development of such a system. With the RFP should go the operational specifications the system must meet for it to show a significant improvement over current systems. Cost limitations on the elements of the system to make it competitive may be included. This paper will demonstrate the use of a computer simulation to estimate these parameters.

The evaluation will assume that the probe system is being employed to maintain a barrier of indefinite length. The barrier is situated so the direction of movement of transitor submarines will be known within a few degrees.

III

DESCRIPTION OF THE MODEL

To make a descriptive simulation of the employment of a system, a scenario is chosen, a tactical policy is prescribed, and assumed values are assigned to the critical parameters. The concept of a passive probe detecting some disturbance phenomena adapts ideally to a barrier operation where the defending force is assigned to detect submarines transiting through a fixed geographical area in a known direction. The fixed geographical area might be defined by channel dimensions with the direction of movement being from the submarine's home port to an obvious operating region. In this model, the course is assumed to be within 30° of the normal to the barrier area and normally distributed with the mean being the perpendicular course. The density of transitor traffic must be adjusted to avoid the forcing of misleading conclusions. In actual practice, even in periods of increased tensions, the volume of such traffic over a two or three day period would be very small. To estimate such a small density would require exceptionally long playing periods to get an "average" reaction to a transit. An increase in density might cause the "dead time" occurring from the time of a contact until the succeeding aircraft arrives on station to become an unduly dominant factor. A density was selected which introduced, on the average, slightly more transitors than scheduled patrol planes. This implies that the area is not saturated with simultaneous transits occurring, but occasionally a transit commences during a dead time interval.

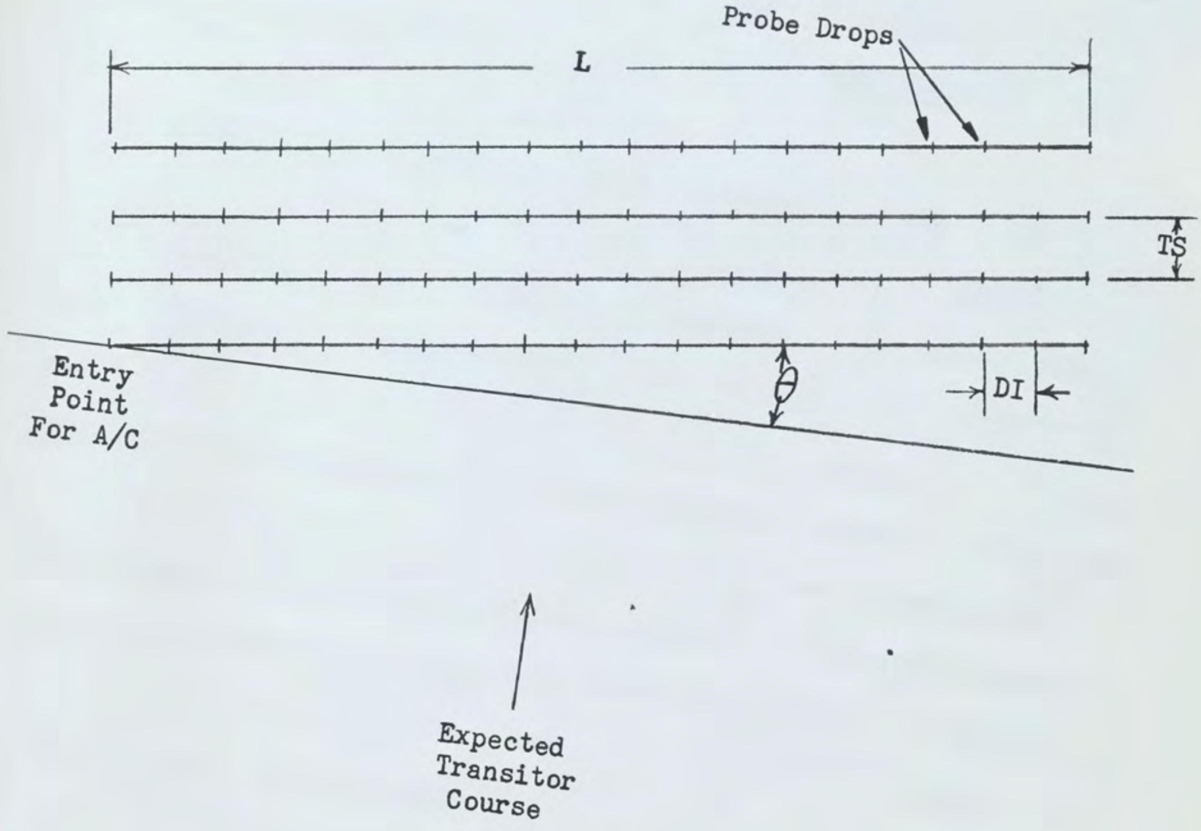
The tactical plan calls for each aircraft to enter the area at a specified entry point and fly a series of parallel legs, dropping probes

at specified drop intervals along each leg until the pattern is completed or until contact is made. If contact is made, the aircraft reverses course and attempts to verify the contact with a series of three closely spaced probes. If the contact is not verified, the aircraft resumes the pattern. If the contact is verified, the aircraft is considered to be committed to the localization and tracking of the contact, and both the sub and the aircraft are dropped from further consideration in the simulation. Accordingly, another aircraft is launched to take up the search and after an appropriate "dead time" arrives on station and starts the search from the common entry point. The search pattern (field) is a series of a predetermined number (NL) of parallel legs extending the length of the barrier (L) and spaced a specified distance apart which is called the track spacing (TS). See Figure 1. Probes are dropped along the legs of the field at intervals called the drop interval (DI). The field orientation is offset from the barrier area by an angle θ. The number of legs (NL) can be varied within the restraints of aircraft endurance on station and stores availability.

In the simulation, a set number of submarines transit the barrier area on randomly selected courses, entering the area at uniformly random points and at random times. The random quantities are generated with the aid of the pseudo-random number generator on the electronic computer. The entry point of the submarine was restricted to not less than 25 miles from either end of the barrier. This guarantees that regardless of course, the submarine will still be in the playing field after crossing all legs of the barrier. A random number between 0 and 1 from a uniform distribution is generated and the entry point computed from:

FIGURE 1

Probe Search Pattern



$$\text{entry point} = 25 + (\text{random number}) \times (L - 50).$$

The game time is divided into N equal intervals where N is the number of submarines in a play of the game and the entry time of each submarine is similarly computed from another uniform random variable. The course is computed from:

$$\text{course} = 1.5708 + (0.5236) \times (\text{random number}).$$

The course is in radians. This random number is taken from a normal distribution of mean zero and variance one. This gives a normally distributed random course with a mean of 90° (perpendicular to the barrier area) and a variance of 30°.

The courses and positions of the transitors are then calculated relative to the field, and the time and position each submarine crosses each leg of the aircraft's pattern is computed. Each probe dropped is then compared with the submarine's time and position of crossing that particular leg to determine if a detection has occurred. If no detection is made, another probe is dropped one drop interval further along the leg, the current time is computed and again each submarine is interrogated to see if detection has occurred. This continues until either the aircraft has reached the end of his pattern, a submarine is contacted, or the allotted game time has expired. See Appendix I for a flow diagram of the program.

Many variable states of nature or characteristics of an air dropped store which could definitely affect the operational performance of the system are not included as variables. It is desired to keep the specifications general enough to be adaptive to widely varying system concepts. If any limiting characteristic of a probe can be offset by a design or engineering change, it is disregarded. Hence, there is no mention of

such items as rate of travel of the probe in air or water. Sea state and visibility are not considered. No system is suggested for the probe to signal a detection nor is a size limitation specified although either of these can significantly affect the altitude, speed and/or flight path of the aircraft.

A detection is assumed to occur if the probe is in the wake of the submarine, and the wake at that position has not deteriorated to less than the critical detection level (i.e., the time interval since passage of the submarine is less than the persistence). Because of the assumptions made of neutral or positive buoyancy of the wake, instantaneous response of the probe, and a vertical probe path, a detection will occur if the aircraft is over any portion of the wake when he drops the probe. The problem then can be reduced to two dimensions and a detection will occur if the aircraft is in an interval of his flight path defined by:

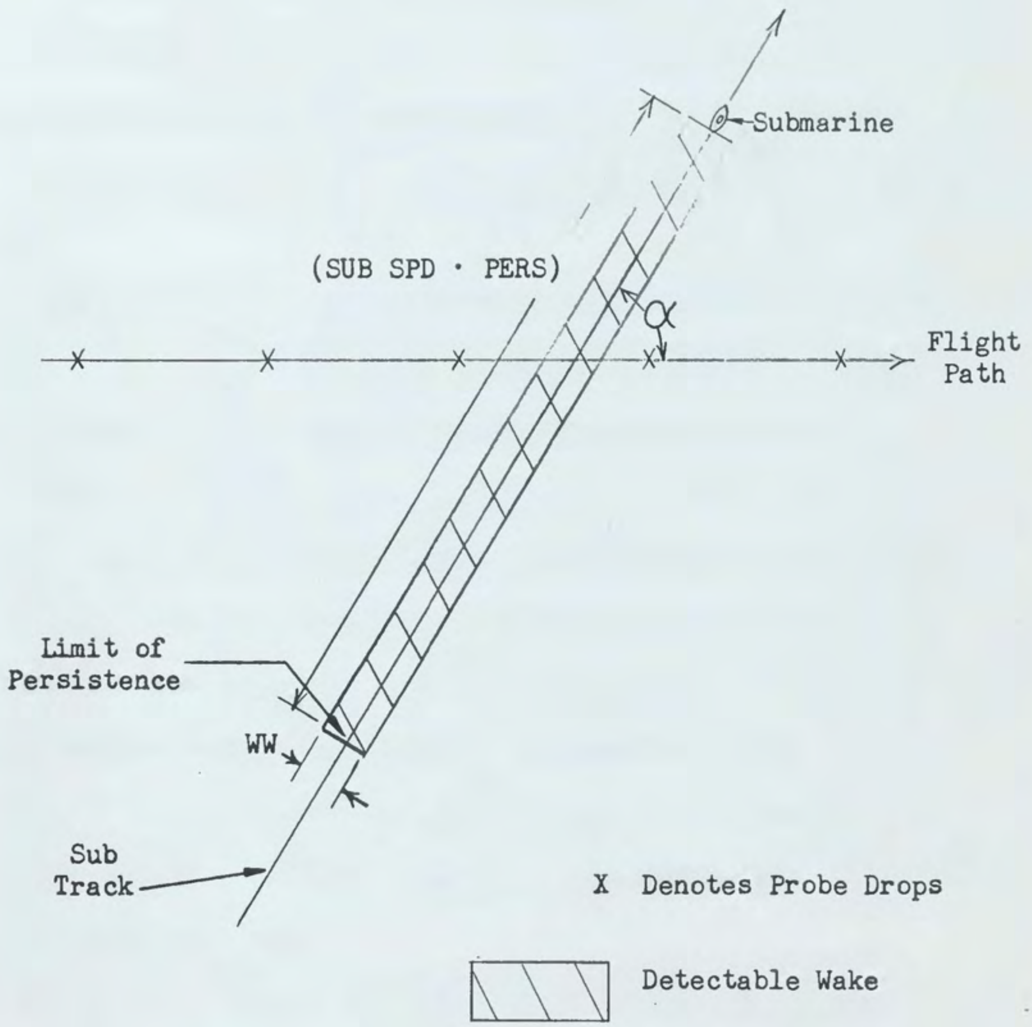
(position submarine crosses that leg) $\pm \frac{1}{2}$(wake width) csc α

where α = (course of submarine) - θ.

See Figure 2.

FIGURE 2

Detectable Wake



IV

SIMULATION RESULTS

4.1 Evaluation of Non-critical Parameters

The model calls for twelve input parameters: the number of submarines in the game, the sub speed, the aircraft speed, dead time required for a relief aircraft to arrive on station (DT), cycle time between scheduled aircraft (CT), the game duration, length of legs (L), number of legs (NL), track spacing (TS), field orientation (θ), width of the detectable wake (WW), and persistence of the wake. Time would not permit an exhaustive set of permutations of all the parameters, so a set of runs was made to identify and assign values to some non-critical parameters.

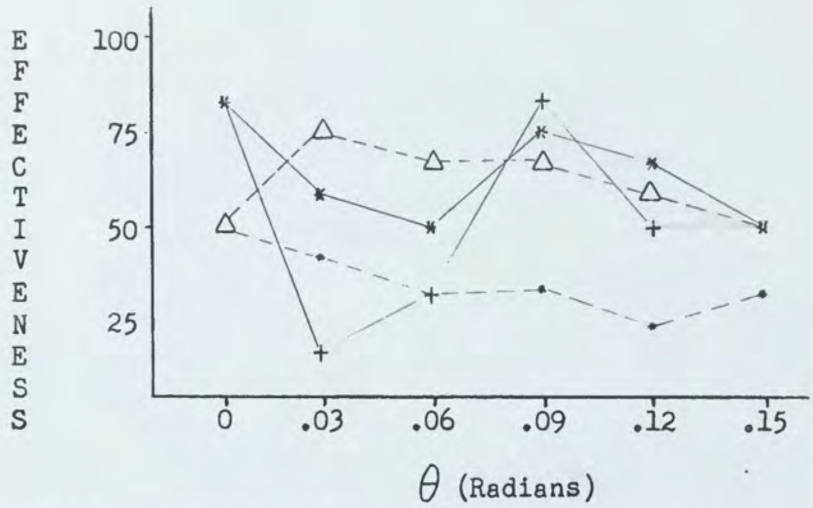
Each "run" consisted of six "plays" of the simulation. In the first group of runs, a single parameter was varied on each play. In this way, the effect of a change in the particular parameter is directly observed since all the other inputs are kept constant. See Appendix II. Plots of the effectiveness (ratio of the number of detections to the number of transits) are used to detect any trend on the variation of this parameter. Figure 3 shows the effect of varying the angle of orientation of the field to the barrier area.

It should be noted that by eliminating Run 8 which combined a long barrier with a depth of only two legs, θ = .09 radians gave an overall high value of effectiveness.

Figure 4 shows the results of varying the track spacing on five runs. With the exception of Run 7, all the runs show peaks or increasing trends at 12 miles. Other runs indicate 12 miles is also good in the same context as Run 7.

FIGURE 3

Effect of Variations of Field Orientation

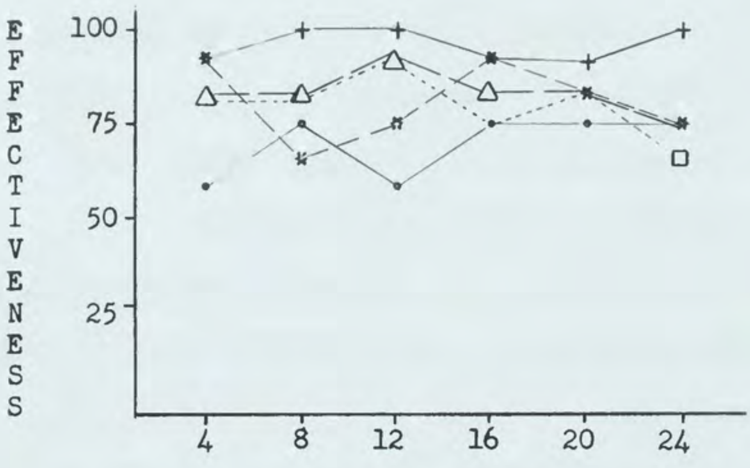


RUN NO.	L	TS	NL	WW	PERS	DI	SUB SPD	GRAPH SYMBOL
2	150	15	4	.2	2	1.0	15	+
5	150	15	6	.2	2	1.0	15	*
8	300	15	2	.2	2	1.0	15	•
12	250	12	4	.2	3	1.0	7	△

All runs use A/C SPEED = 150 knots, DT = 2 hours, CT = 8 hours.

FIGURE 4

Effect of Variation of Track Spacing



RUN NO.	L	θ	NL	WW	PERS	DI	SUB SPD	GRAPH SYMBOL
4	150	.1	4	.4	3	.5	15	+
7	150	.1	4	.2	3	.75	15	•
10	250	.09	4	.2	3	.5	15	△
11	250	.09	4	.2	3	.5	7	*
13	150	.09	4	.2	3	.5	5	□

All runs use A/C SPEED = 150 knots, DT = 2 hours, CT = 8 hours.

Run 14 varied the number of legs flown on a 300 mile barrier. There was no pronounced peak and in light of Run 8, the value of the 300 mile barrier was questionable, so most of the runs were made with 4 legs and a shorter length.

The second group of runs held the inputs constant for each of the six plays in every run, but parameters were changed between runs. Appendix III Table 1 shows the results of the runs with a wake width of 0.4 and 0.3 miles. Such a wide detection area makes most other parameters insignificant but it should be noted that Run 3 showed a sharp decrease in effectiveness. Run 3 differed from Run 6 only in density of submarine traffic. Run 6 showed an effectiveness of the system of 79.2% against an average of one submarine every six hours. Run 3, however, showed an effectiveness of only 46.8% against an average of one submarine every three hours. Excepting Run 3, it appears that with a wake width of 0.4 miles and a drop interval of 0.5 miles, tactics were unimportant. No further considerations were made of wakes of this width. Run 3, however, showed that even with this wide wake, the system could be saturated.

Appendix III, Table 2 summarizes the results of the runs using a wake width of 0.2 miles. The runs are ordered by effectiveness, and a definite pattern emerges. Runs longer than 250 miles in length tend to lose effectiveness as shown by Runs 36 and 38. Reducing submarine density has negligible effect. (See pairs 25 and 43, and 41 and 42.) Increasing the aircraft speed (see pair 30 and 39) also does not appreciably alter the effectiveness. From these results, the following parameter values were assumed for making a more detailed analysis:

aircraft speed = 150 knots

dead time = 2 hours

cycle time = 8 hours

track spacing = 12 miles

field orientation = 0.09 radians

length of field = 250 miles

4.2 Optimization of Critical Parameters

With the established parameters determined by the aforementioned runs, another set of runs was made in which the remaining parameters (NL, DI, WW) were varied over three submarine transit speeds. These results are shown in Appendix IV. As it would seem, the effectiveness increases with an increase in the number of legs flown, but for more than fours legs, the gain is small. The difference between a two and three hour persistence is small and inconsistent, implying that the lingering of the disturbance is of less importance than the lateral range in the range of parameter values considered. Consistently throughout the set, the smallest drop interval gave the highest effectiveness. Efforts to substitute more legs with a greater drop interval caused a loss in effectiveness.

These results provide a guide for establishing specifications for an aircraft-expendable probe system for use in barrier operations. Under the assumptions made and the values of this example, appropriate specifications should assure that the barrier effectiveness will be near the level indicated. That is, the probe must be able to detect the submerged trail of a submarine within 0.1 mile on either side of its track for up to two hours after submarine passage. Given that the probe is developed,

then the aircraft-probe system must be compatible with the total stores requirements and must be able to meet the technical demands such as rapid probe ejections, probe data interpretation, etc. The forecast of a probable failure of the system to meet any one of these requirements would call for a reconsideration of the necessity of the barrier or the effectiveness of other systems, and might suggest a rejection of further development of the probe system.

V

COMPARATIVE EFFECTIVENESS

There remains to be established a suitable scale for measuring this system for comparison with other systems possibly working on different physical principles but with the same objectives. Such a scale might give measurements in terms of miles of barrier versus number of skilled and/or unskilled personnel for a given level of effectiveness. Another scale, which will be outlined in this paper, is cost per day per mile of barrier for a given level of effectiveness. There is no apparent "best" measure of effectiveness always applicable to all systems, but the measure used should be determined by the "current critical parameter" whether it be number of skilled personnel available, vehicles on hand, money, or other factor.

Consider the employment of expendable probes herein described in a cold war situation. It is reasonable to assume that the limiting factor would be cost, and hence the comparison of systems to be used to prosecute the barrier would be made on a cost basis for a given effectiveness. Appendix IV indicates that the system could be reasonably expected to attain a level of effectiveness of about 80-85%. All combinations of characteristics for a given set of sensitivity parameters can be explored to determine the best combination for any ratio of costs.

Suppose the requirement were given to select a system for development which could maintain a barrier of an undetermined length with an effectiveness of about 80%. Contractor estimates and past experience would be consulted and system operating costs would be approximated.

Assume these estimates could be made in the form:

aircraft operating costs = X dollars per hour on station

probe costs = Y dollars per unit store

$$\text{readiness cost} = \begin{cases} \text{Z dollars per day for DT} = 2 \\ \text{Z' dollars per day for DT} = 3 \end{cases}$$

Included in the aircraft operating costs with the actual operating costs are all the additional personnel, facility, and support costs necessary to maintain the required level of aircraft coverage on station. The probe costs include storage facilities, dispenser equipment, and other related expenses. The readiness cost estimate represents the daily increase in operating costs accompanying a state of readiness necessary to support a reduced dead time requirement. So, for a given level of effectiveness, the system costs would be:

$$\text{system cost/day/mile} = (^1/_L) \Big[X \cdot (\text{estimated hours on station per day}) + Y \cdot (\text{estimated stores dropped per day}) + Z \Big].$$

From Appendix IV, the combinations of tactics which would give the desired level of effectiveness can be isolated and analyzed for variables which would affect the system cost. This information is shown in Appendix V.

In Appendix V, the aircraft requirements of the system are shown in three categories. Category I requires an aircraft with sufficient stores capacity and endurance to fly a six leg pattern dropping probes at ½ mile intervals. This corresponds to 3000 probes and 10.56 hours on station at a speed of 150 knots. Category II requires four leg patterns (2000 probes and 7.01 hours on station) and category III, three legs (1500 probes and 5.23 hours on station). For each category, the stipulated conditions of system sensitivity (persistence), state of

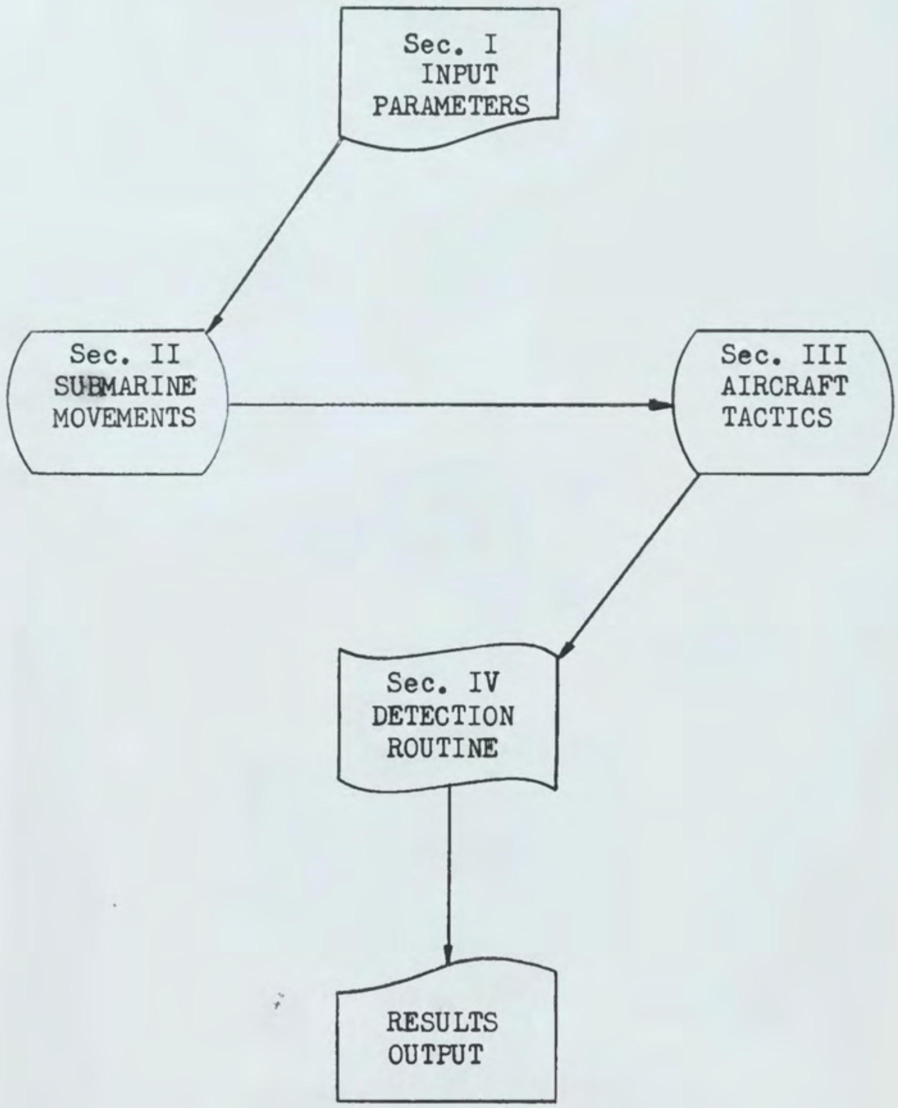
readiness (dead time), tactics (number of legs) and opposition (range of transitor speeds) are posed and simulation data presented. From this information, the expected cost of the system for each set of stipulated conditions is made.

Appendix V indicates, as would be expected, that for each set of stipulated conditions, an increase of the number of legs flown, which would inherently increase the average on-station time and the number of probes dropped, increases the effectiveness. For a given level of effectiveness, however, tradeoffs may be beneficial. For example, if the required level of effectiveness is 80%, and $Z > Z' + .83 X + 230 Y$, then a six leg pattern at a reduced readiness level (corresponding to 3 vice 2 hours dead time following a contact) would be less expensive.

With data in this form and updated estimates of aircraft and probe costs, the planner has an analytical aid to assist him in making a comparison between proposed or existing systems for accomplishing the mission.

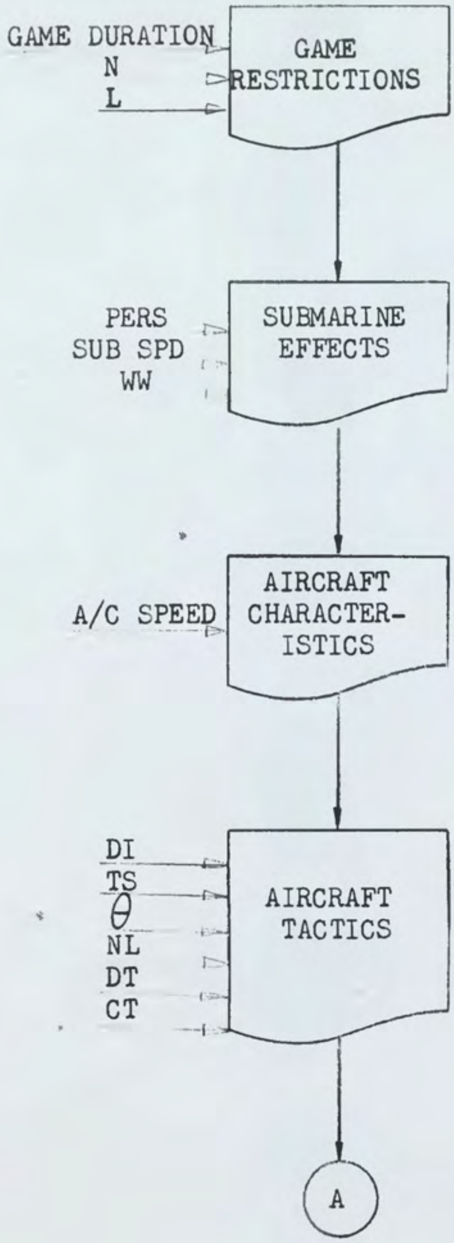
APPENDIX I

Flow Diagram



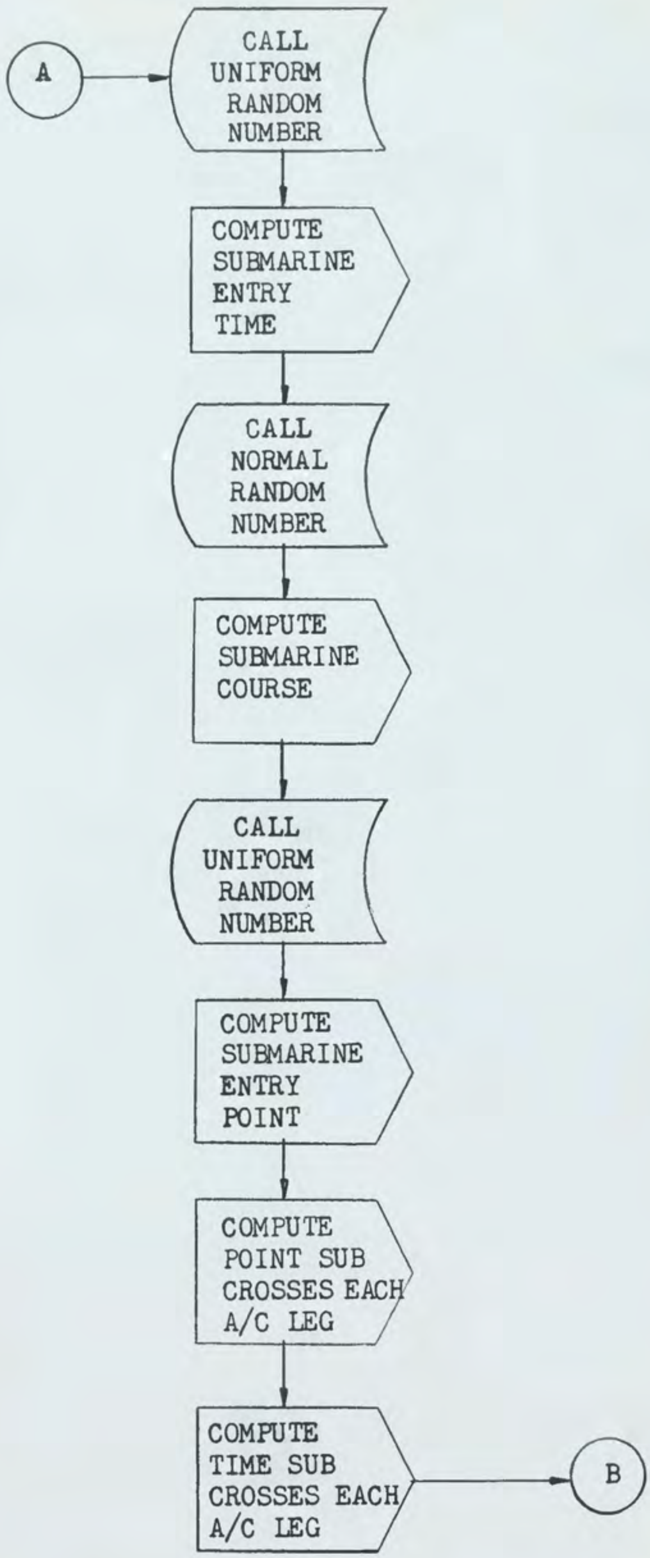
Section I

INPUT PARAMETERS



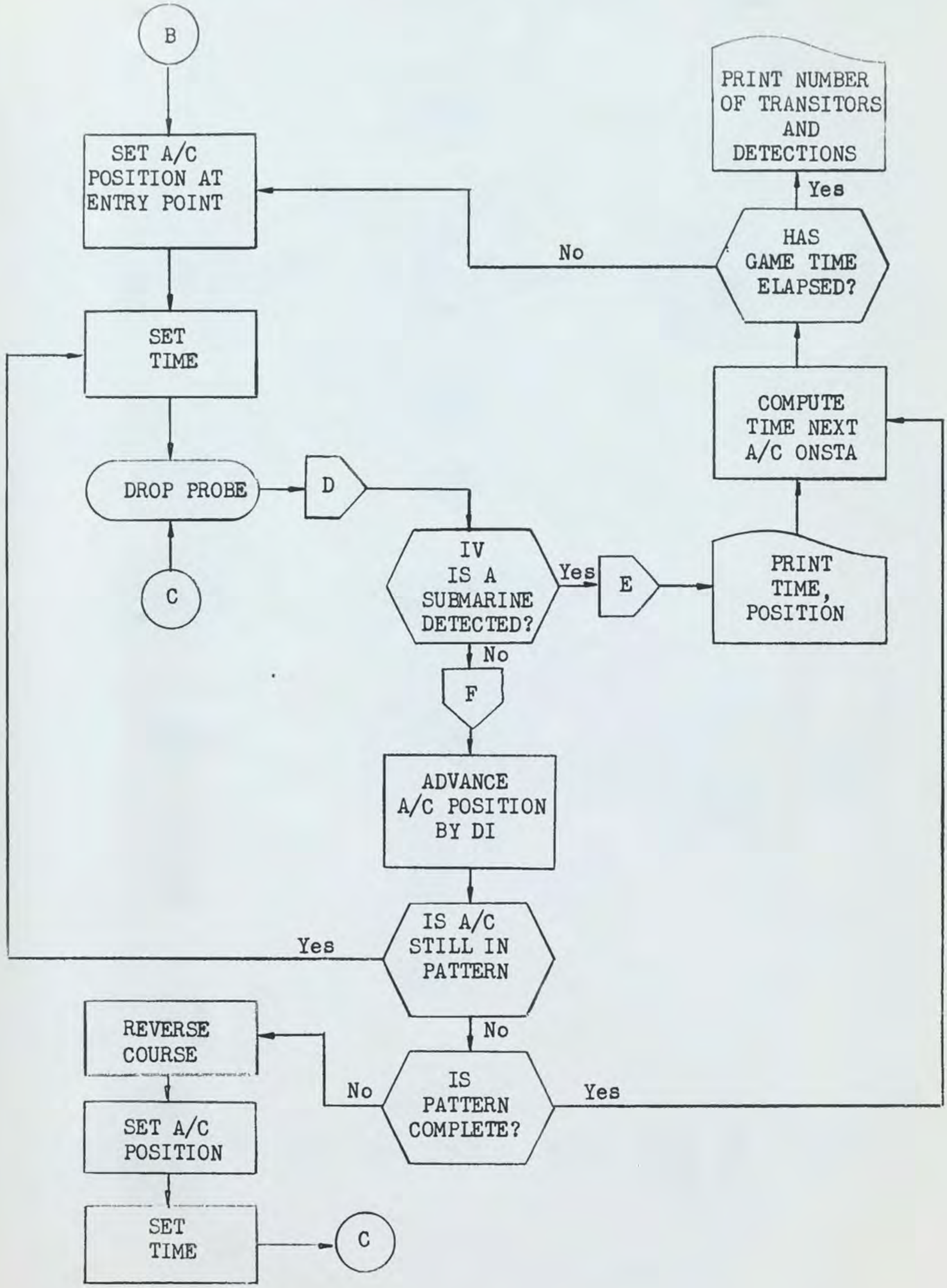
Section II

SUBMARINE MOVEMENTS

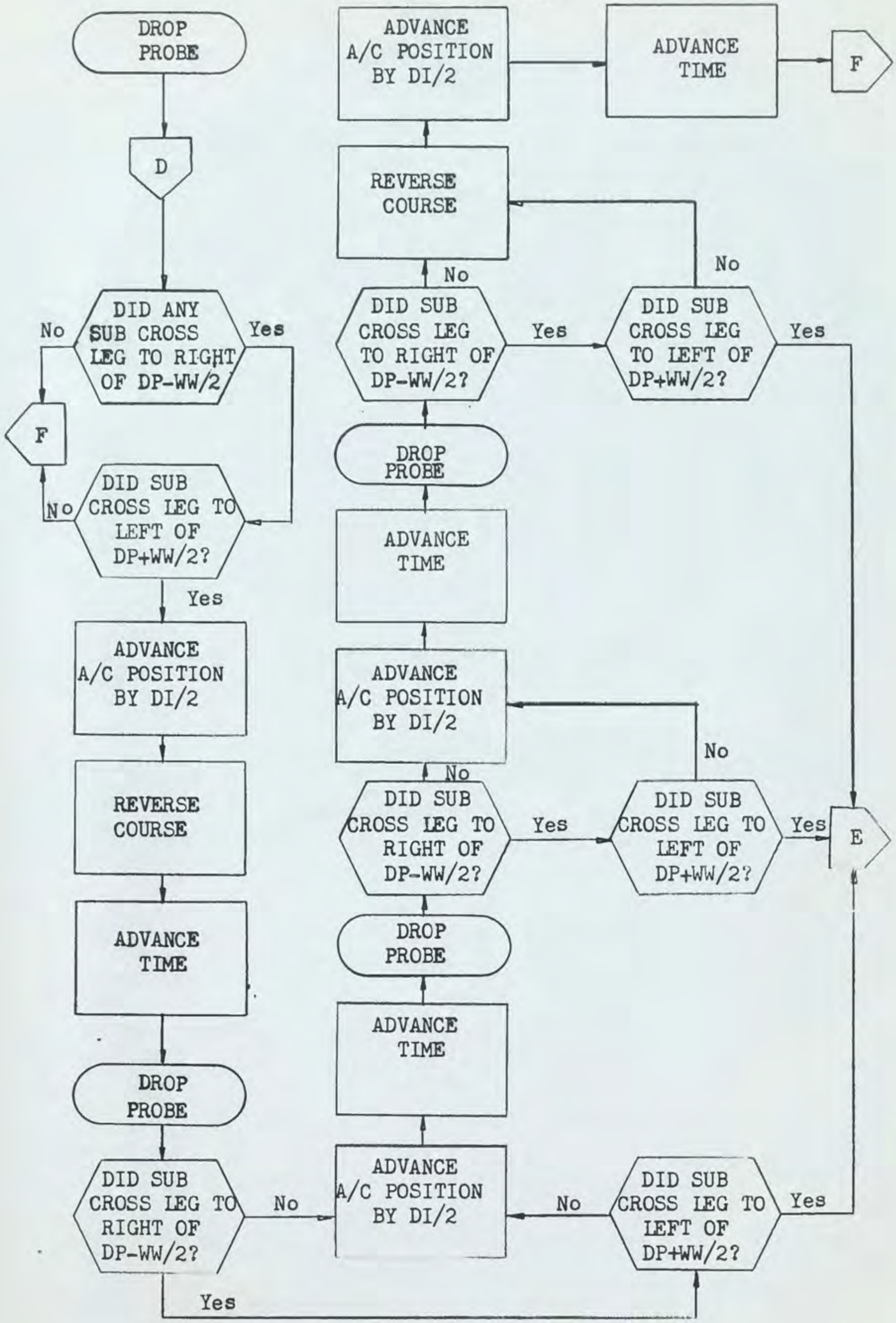


Section III

AIRCRAFT TACTICS



DETECTION ROUTINE



APPENDIX II

<table>
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θ</td></tr>
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</table>

All runs have A/C SPD = 250 knots, DT = 2 hours, CT = 8, and DI = 1.0 miles.
All runs have WW = 0.2 miles except Run 4.
*WW = 0.4 miles in Run 4.

APPENDIX III

Table 1

EFF. RANGE	RUN NO.	A/C SPD	CT	L	TS	WW	θ	DI	SUB SPD	SUBS PER DAY	EFF.
86-90	26	150	8	250	12	.4	.09	.5	7	4	89.0
81-85	1	150	8	150	4	.4	.1	.5	15	6	83.3
76-80	40	300	12	300	12	.4	.09	.5	7	4	80.5
	6	150	8	250	15	.4	.1	1.0	15	4	79.2
	9	150	8	250	15	.3	.1	1.0	15	4	75.0
<75	3	150	8	250	15	.4	.1	1.0	15	8	46.8

On all runs, DT = hours, NL = 4, PERS = 3 hours.

APPENDIX III

Table 2

EFF. RANGE	RUN NO.	DT	CT	NL	L	PERS	DI	SUB SPD	SUBS PER DAY	EFF.
81-85	25	2	8	4	250	3	.5	7	4	83.3
	31	2	8	4	250	3	.5	7	4	83.3
	43	2	8	4	250	3	.5	7	2	80.5
76-80	35	2	8	4	250	3	.5	15	4	79.2
	36	2	8	4	250	3	.5	5	4	79.2
	15	2	12	4	250	3	.5	7	4	79.2
	27	2	8	4	250	3	.5	7	4	76.4
	33	2	12	4	250	3	.5	7	4	76.4
71-75	42	3	8	4	250	3	.5	7	2	75.0
	34	2	12	4	250	3	.5	15	4	75.0
	41	3	8	4	250	3	.5	7	4	73.6
	38	2	8	4	300	3	.5	5	4	71.8
66-70	29	2	8	4	250	2	.75	7	4	68.1
	32	2	8	4	250	3	.75	7	4	68.1
	17	3	8	4	250	2	.75	15	4	66.7
61-65	18	3	8	4	250	2	.75	7	4	62.5
	28	2	8	4	250	2	.75	15	4	61.1
51-60	19	3	8	4	250	3	.75	7	4	59.8
	30	2	8	4	250	3	1.0	7	4	54.3
	39*	2	8	4	250	3	1.0	7	4	52.8
	23	2	12	4	250	3	1.0	7	4	51.5
35-50	37	2	12	6	225	3	1.5	7	4	47.3
	16	3	8	1	500	2	.5	7	4	45.8
	20	2	12	1	500	3	.5	7	4	40.3
<35	22	2	12	1	150	3	.5	7	4	30.5
	21	2	12	3	225	3	1.5	7	4	25.0

TS = 12 miles, WW = 0.2 miles, θ = 0.09 radians on all runs
Aircraft speed = 150 knots except Run 39
*Aircraft speed = 300 knots on Run 39

APPENDIX IV

EFF. RANGE	RUN NO.	TRANSITOR SPEED									EFF.
		15 KNOTS			7 KNOTS			5 KNOTS			
		NL	PERS	DI	NL	PERS	DI	NL	PERS	DI	
86-90	98	6	2	.5							88.9
81-85	62							6	2	.5	84.6
	82	6	3	.5							83.3
	53				6	2	.5				83.3
	25				4	3	.5				83.3
	93*	6	2	.5							83.3
	52				6	3	.5				81.9
	61							6	3	.5	81.9
	48				4	2	.5				81.9
	92*				6	2	.5				81.9
	46	4	2	.5							80.6
	73							4	3	.5	80.6
76-80	91*							6	2	.5	79.3
	35	4	3	.5							79.3
	88	3	2	.5							77.8
	94				3	2	.5				77.8
	97*	3	2	.5							77.8
	58							4	2	.5	77.8
	84	3	3	.5							77.8
	71				6	2	1.0				77.8
	81				3	3	.5				77.8
	51				6	2	.75				76.4
	96*				3	2	.5				76.4
	65							3	3	.5	76.4
	66							3	2	.5	76.4

APPENDIX IV
Continued

EFF. RANGE	RUN NO.	TRANSITOR SPEED									EFF.
		15 KNOTS			7 KNOTS			5 KNOTS			
		NL	PERS	DI	NL	PERS	DI	NL	PERS	DI	
71-75	75							6	3	1.0	75.0
	95*							3	2	.5	73.6
	44	4	3	.75							70.9
66-70	69							4	2	.75	68.1
	80	4	2	1.0							68.1
	63							6	3	.75	68.1
	45	4	3	1.0							66.7
	49				4	2	.75				66.7
	70				6	3	1.0				66.7
	74							6	2	1.0	66.7
	79	4	2	.75							66.7
	50				6	3	.75				65.3
	59							4	2	.75	65.3
	60							4	2	1.0	65.3
	64							6	2	.75	65.3
	72				3	1	.75				65.3
56-65	55				3	2	.75				59.6
	56							4	3	.75	59.6
	57							4	3	1.0	58.3
	87				4	2	1.0				58.3
	76							3	2	.75	58.3
	78	4	1	1.0							57.0
51-55	54				3	3	.75				54.1
	85	3	3	.75							54.1
	68							3	2	1.0	54.1
	89	3	2	.75							54.1
	77							3	3	.75	52.8
<50	90	3	2	1.0							48.6
	86	3	3	1.0							46.8
	67							3	3	1.0	44.5

TS = 12 miles, WW = 0.2 miles, θ = 0.09 radians, A/C SPD = 150 knots, CT = 8 hours, DT = 2 hours except where noted.
*DT = 3 hours

APPENDIX V

	STIPULATED CONDITIONS			SIMULATION RESULTS					EXPECTED COST/DAY/MILE
CAT.	PERS	DT	SUB SPD	RUN NO.	HRS. ON STA	STORES PER DAY	EFF.	AVE. EFF.	
I	3	2	5 7 15	61 52 82	21.51 21.35 19.89	6066 6073 5839	81.9 81.9 83.3	82.4	$\frac{20.91X+5992Y+Z}{250}$
	2	2	5 7 15	62 53 98	20.77 21.01 19.75	5835 5989 5888	84.6 83.3 88.9	85.6	$\frac{20.51X+5904Y+Z}{250}$
	2	3	5 7 15	91 92 93	18.08 16.98 16.66	5022 4894 4885	79.3 81.8 83.3	81.5	$\frac{17.24X+4934Y+Z'}{250}$
II	3	2	5 7 15	73 25 35	16.33 16.36 16.54	4715 4660 4738	80.5 83.3 79.3	81.0	$\frac{16.41X+4704Y+Z}{250}$
	2	2	5 7 15	58 48 46	16.60 16.32 16.31	4699 4672 4698	77.8 81.9 80.6	80.1	$\frac{16.41X+4690Y+Z}{250}$
III	3	2	5 7 15	65 81 84	13.95 14.32 14.20	3914 3907 3983	76.4 77.8 77.8	77.3	$\frac{14.16X+3935Y+Z}{250}$
	2	2	5 7 15	66 94 88	13.89 14.06 14.26	3910 3920 3999	76.4 77.8 77.8	77.3	$\frac{14.07X+3943Y+Z}{250}$
	2	3	5 7 15	95 96 97	12.08 12.20 12.25	3393 3430 3417	73.6 76.4 77.8	75.9	$\frac{12.18X+3413Y+Z'}{250}$